POWER MODULE WITH VOLTAGE OVERSHOOT LIMITING

BACKGROUND OF THE INVENTION

Field of the Invention

This disclosure is generally related to electrical power systems, and more particularly to power module architectures suitable for rectifying, inverting and/or converting electrical power between power sources and loads.

Description of the Related Art

Power modules are typically self-contained units that transform and/or condition power from one or more power sources for supplying power to one or more loads. Power modules commonly referred to as "inverters" transform direct current (DC) to alternating current (AC), for use in supplying power to an AC load. Power modules commonly referred to as "rectifiers" transform AC to DC. Power modules commonly referred to as "DC/DC converters" step up or step down a DC voltage. An appropriately configured and operated power module may perform any one or more of these functions. The term "converter" is commonly applied generically to all power modules whether inverters, rectifiers and/or DC/DC converters.

Current flowing through various inductive paths within the module transiently stores energy which increases energy loss, reduces efficiency, and generates heat. When the flow of current changes, as in such a high frequency switching environment, large voltage overshoots often result, further decreasing efficiency. These large voltage overshoots typically reduce the power rating of the power module or require the use of circuitry devices with higher ratings than would otherwise be required, thus significantly increasing the cost of the power module.

To minimize the negative effects of current gradients, noise and voltage overshoots associated with the switching process of the module, large

capacitors are generally placed in a parallel arrangement between the positive and negative DC connections or from each DC connection to a ground or chassis. These large capacitors are commonly referred to as “X” or “Y” capacitors. Relatively large external capacitors of about around 100 micro Farads are needed. By “external” it is meant that the element referred to is located outside of a power module. High frequency noise, and voltage overshoots that are initiated in the module by the switching process travel away from the source of the noise and voltage overshoots. A low impedance network may be used to provide a return path for the high frequency energy associated with noise and voltage overshoots. The further the energy travels, the more difficult it is to provide a low impedance network to return the energy. Therefore, capacitors attached between the positive and negative DC connections or from the DC connections to ground must be relatively large to minimize the impact of noise, and voltage overshoots. In addition, these external capacitors typically cause stray inductance, which renders the capacitor ineffective at frequencies higher than about 10 kHz.

These and other problems are avoided and numerous advantages are provided by the method and device described herein.

SUMMARY OF THE INVENTION

The disclosure is directed to an architecture for a power module that limits or dampens voltage overshoot, permitting the power module to handle larger loads, and/or allowing the use of circuitry with lower ratings than would otherwise be required and thus reducing cost.

In one aspect, a power module comprises: a lead frame forming at least a portion of a module housing; a first set of terminals accessible from an exterior of the lead frame; a second set of terminals accessible from the exterior of the lead frame; a positive DC bus received at least partially in the module housing; a negative DC bus received at least partially in the module housing; a number of high side switches received in the module housing and selectively electrically

coupling a first one of the first set of terminals to respective ones of the second set of terminals; a number of low side switches received in the module housing and selectively electrically coupling a second one of the first set of terminals to respective ones of the second set of terminals; and at least one capacitor electrically coupled between the positive DC bus and the negative DC bus.

In another aspect, a power system comprises: a lead frame; a plurality of electrical terminals carried by the lead frame; a first bus bar coupled to the lead frame; a second bus bar coupled to the lead frame; a high side substrate coupled to the lead frame, the high side substrate comprising a number of electrically conductive high side collector areas and a number of electrically conductive high side emitter areas, the high side emitter areas electrically isolated from the high side collector areas; a low side substrate coupled to the lead frame, the low side substrate comprising a number of electrically conductive low side collector areas and a number of electrically conductive low side emitter areas, the low side emitter areas electrically isolated from the low side collector areas; a number of high side switches physically coupled to the high side substrate; a number of low side switches physically coupled to the low side substrate; and a number of capacitors, each of the capacitors electrically coupled between one of the high side collector areas and one of the low side emitter areas.

In a further aspect, method of forming a power module comprises: providing a lead frame; coupling a substrate comprising a high side and a low side to the lead frame, the high side comprising a number of high side collector areas and a number of high side emitter areas electrically isolated from the high side collector areas, the low side comprising a number of low side collector areas and a number of low side emitter areas electrically isolated from the high side collector areas; mounting a number of high side switches to the high side of the substrate; mounting a number of low side switches to the low side of the substrate; surface mounting at least one capacitor to a low side emitter area; and surface mounting the at least one capacitor to a high side collector area.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, identical reference numbers identify similar elements or acts. The sizes and relative positions of elements in the drawings are not necessarily drawn to scale. For example, the shapes of various elements and angles are not drawn to scale, and some of these elements are arbitrarily enlarged and positioned to improve drawing legibility. Further, the particular shapes of the elements as drawn, are not intended to convey any information regarding the actual shape of the particular elements, and have been solely selected for ease of recognition in the drawings.

Figure 1 is an isometric view of a power module comprising a housing, integrated cold plate, DC bus terminals, AC phase terminals, and power semiconductor devices.

Figure 2A is an isometric view of the power module of Figure 1 with a cover removed and some portions broken or removed to show the DC bus, the AC bus, and the power semiconductor devices carried by various regions on a substrate

Figure 2B is a top plan view of the power module of Figure 2A showing a representative sampling of wire bonds electrically connecting various power semiconductor components, buses, and layers in the substrate as an inverter.

Figure 3 is a schematic cross sectional view of one embodiment of the DC bus comprising a pair of L-shaped vertical DC bus bars spaced by an electrical insulation.

Figure 4 is a schematic cross sectional view of one embodiment of the DC bus comprising a pair of generally planar DC bus bars spaced by an electrical insulation.

Figure 5A is a partial isometric view of a portion of a low side of the power converter illustrating the surface mounting of snubber capacitors to a low side emitter area of the substrate.

Figure 5B is an isometric view of a portion of a high side of the substrate illustrating the surface mounting of the snubber capacitors of Figure 5B to high side collector area of the substrate.

Figure 6 is an electrical schematic of the switches, freewheeling diodes, and decoupling capacitors according to an illustrated embodiment.

DETAILED DESCRIPTION OF THE INVENTION

In the following description, certain specific details are set forth in order to provide a thorough understanding of various embodiments of the invention. However, one skilled in the art will understand that the invention may be practiced without these details. In other instances, well-known structures associated with power modules, power semiconductors and controllers have not been shown or described in detail to avoid unnecessarily obscuring descriptions of the embodiments of the invention.

Unless the context requires otherwise, throughout the specification and claims which follow, the word "comprise" and variations thereof, such as, "comprises" and "comprising" are to be construed in an open, inclusive sense, that is as "including, but not limited to."

The headings provided herein are for convenience only and do not interpret the scope or meaning of the claimed invention.

Figures 1, 2A, and 2B show a base power module 10, generally comprising: a lead frame or housing 12, an integrated cold plate 14 attached to the housing 12 via bushings 15, a DC bus 16, an AC bus 18; circuitry 20 electrically coupled between the DC bus 16 and AC bus 18, forming a high side 20a and a low side 20b of the power module 10. The base power module 10 may further include one or more gate drivers 22 (Figure 9) for driving some of the power semiconductors 20.

Two sets of DC bus terminals 24, 26 extend out of the housing 12. In some applications one set of DC bus terminals 24 is electrically coupled to a

positive voltage or high side of a power source or load and the other set of DC bus terminals is 26 is electrically coupled to a negative voltage or low side of the power source or load. In other applications, the DC bus terminals 24, 26 are electrically coupled to respective DC bus terminals 24, 26 on another power module. A set of AC phase terminals comprises three pairs of AC bus phase terminals 28a, 28b, 30a, 30b, 32a, 32b, extending out of the housing 12. In some applications, one pair of AC phase terminals is coupled to a respective phase (A, B, C) of a three phase power source or load. In other applications, some of the AC phase terminals are interconnected across or between the pairs, and coupled to power sources or loads.

Figure 3 shows a schematic cross-sectional view of the power module 10 taken along section line 3-3 of Figure 2A. Figure 3 is not an exact cross-sectional view, but has been modified to more accurately represent the electrical connections which would otherwise not be clearly represented in the Figure 3.

The integrated cold plate 14 comprises a metal base plate 39, a direct copper bonded (DCB) substrate 40 which is attached to the metal base plate by a solder layer 41. A cooling header 42 including a number of cooling structures such as fins 42a, one or more fluid channels 42b, a fluid inlet 42c and a fluid outlet 42d for providing fluid connection flow to and from the fluid channels 42b, respectively.

The DCB substrate 40 typically comprise a first copper layer 40a, a ceramic layer 40b and a second copper layer 40c which are fused together. The second copper layer 40c may be etched or otherwise processed to form electrically isolated patterns or structures, as is commonly known in the art. For example, the second copper layer 40c may be etched to form regions of emitter plating 43a (*i.e.*, emitter plating areas or emitter areas) and collector plating 44a (*i.e.*, collector plating areas or collector areas) on a low side of the power module 10 (*i.e.*, side connected to DC bus bar 34). Also for example, the second copper layer 40c may

be etched to form regions of emitter plating 43b and collector plating 44b on the high side of the power module 10 (*i.e.*, the side connected to DC bus bar 36).

A conductive strip 45 or wire bonds may extend between the collector plating 44a of the low side and the emitter plating 43b of the high side, passing through respective passages 46 formed under the DC bus bars 34, 36. As illustrated, the conductive strip 45 has be exaggerated in length on the low side of the power module 10 to better illustrate the electrical connection with the collector plating 44a.

Power semiconductor devices 20 are attached to the various structures formed in the second copper layer 40c via a solder 47. The power semiconductor devices 20 may include one or more switches for example, transistors 48 such as integrated bipolar gate transistors (IGBTs) or metal oxide semiconductor field effect transistors (MOSFETS). The power semiconductor devices 20 may also include one or more diodes 50. The power semiconductor devices 20 may have one or more terminals directly electrically coupled by the solder 47 to the structure on which the specific circuit element is attached. For example, the collectors of IGBTs 48 may be electrically coupled directly to the collector plating 44a, 44b by solder 47. Similarly, the cathodes of diodes 50 may be electrically coupled directly to the collector plating 44a, 44b by solder 47.

The DC bus 16 comprises a pair of L-shaped or vertical DC bus bars 34a, 36a. The upper legs of the L-shaped DC bus bars 34a, 36a are parallel and spaced from one another by the bus bar insulation 38. The lower legs of the L-shaped DC bus bars 34, 36 are parallel with respect to the substrate 40 to permit wire bonding to appropriate portions of the substrate. For example, the negative DC bus bar 34a may be wire bonded to the emitter plating 43a of the low side, while the positive DC bus bar 36a may be wire bonded to the collector plating 44b of the high side. The emitters of the IGBTs 48 and anodes of the diodes 50 may be wire bonded to the respective emitter plating 43a, 43b. Wire bonding in combination with the rigid structure of the DC bus 16 and housing 12 may also

eliminate the need for a hard potting compound typically used to provide rigidity to protect solder interfaces. For low cost, the copper layers 40a and 40c may be nickel finished or aluminum clad, although gold or palladium may be employed at the risk of incurring higher manufacturing costs.

Figure 4 shows another embodiment of the DC bus 16 for use in the power module 10, the DC bus 16 comprising a pair of generally planar DC bus bars 34b, 36b parallel and spaced from one another by a bus bar insulation 38. The DC bus bars 34b, 36b are horizontal with respect to a substrate 40 (Figures 1 and 2), with exposed portions to permit wire bonding to the various portions of the substrate 40.

Because the DC bus bars 34, 36 are parallel, counter flow of current is permitted, thereby canceling the magnetic fields and their associated inductances. In addition the parallel DC bus bars 34, 36 and bus bar insulation 38 construct a distributed capacitance. As will be understood by one of ordinary skill in the art, capacitance dampens voltage overshoots that are caused by the switching process. Thus, the DC bus bars 34, 36 of the embodiments of Figures 3 and 4 create a magnetic field cancellation as a result of the counter flow of current, and capacitance dampening as a result of also establishing a functional capacitance between them and the bus bar insulation 38.

As best illustrated in Figures 5A, 5B and 6, the circuitry 20 includes a number of snubber capacitors 53 that are electrically coupled between the DC bus bars 34, 36 to clamp voltage overshoot. For example, some of the snubber capacitors 53 are electrically coupled directly (*i.e.*, surface mounted) to the emitter plating 43a on the low side 20b of the power module 10 and are electrically coupled directly (*i.e.*, surface mounted) to the collector plating 44b on the high side 20a of the power module 10. While the Figures show two snubber capacitors for each switching pair combination, the power module 10 may include fewer or a greater number of snubber capacitors as suits the particular application. Significant savings may be realized by effective clamping of voltage overshoot.

For example, if switching is maintained below approximately 900V, a transformer may be eliminated. The snubber capacitors 53 can be soldered in the same operation as the soldering of the substrate 40 to the cold plate 14, or the soldering of other elements of the circuitry 20 to the substrate 40, simplifying manufacturing and reducing costs.

As best illustrated in Figures 2A and 2B, the circuitry 20 also includes a number of decoupling capacitors 55 which are electrically coupled between the DC bus bars 34 or 36 and ground to reduce EMI. In contrast to prior designs, the decoupling capacitors 55 are located on the substrate 40 inside the housing 12. For example, some of the decoupling capacitors 55 are electrically coupled directly to the emitter plating 43a on the low side 20b of the power module 10 and some of the decoupling capacitors 55 are electrically coupled directly to the collector plating 44b on the high side 20a of the power module 10. The decoupling capacitors 55 can be soldered in the same operation as the soldering of IGBTs 48 and 50 to the substrate 40.

As best illustrated in Figures 1 and 2A, the DC bus bars 34, 36 each include three terminals 24, 26, spaced along the longitudinal axis, to make electrical connections, for example, to a DC power source. Without being restricted to theory, Applicants believe that the spacing of the terminals 24, 26 along the DC bus bars 34, 36 provides lower inductance paths within the DC bus bars 34, 36 and to the external DC voltage storage bank.

In contrast to typical power modules, the DC bus bars 34, 36 are internal to the housing 12. This approach results in better utilization of the bus voltage, reducing inductance and consequently permitting higher bus voltages while maintaining the same margin between the bus voltage and the voltage rating of the various devices. The lower inductance reduces voltage overshoot, and problems associated with voltage overshoot such as device breakdown. The increase in bus voltage permits lower currents, hence the use of less costly devices. The bus bar insulation 38 between the DC bus bars 34, 36 may be

integrally molded as part of the housing 12, to reduce cost and increase structural rigidity. The DC bus bars 34, 36 may be integrally molded in the housing 12, or alternatively, the DC bus bars 34, 36 and bus bar insulation 38 may be integrally formed as a single unit and attached to the housing 12 after molding, for example, via post assembly.

The power semiconductors 20 are directly mounted on the substrate 40 which is directly attached to the cold plate 14 via solder layer 41, the resulting structure serving as a base plate. The use of a cold plate 14 as the base plate, and the direct mounting of the power semiconductors 20 thereto, enhances the cooling for the power semiconductors 20 over other designs, producing a number of benefits such as prolonging the life of capacitors 55.

The power semiconductors 20 are operable to transform and/or condition electrical power. As discussed above, the power semiconductors 20 may include switches 48 and/or diodes 50. The power semiconductors 20 may also include other electrical and electronic components, for example, capacitors 55 and inductors, either discrete or formed by the physical layout. The power module 10 and power semiconductors 20 may be configured and operated as an inverter (DC→AC), rectifier (AC→DC), and/or converter (DC→DC; AC→AC). For example, the power module 10 and/or power semiconductors 20 may be configured as full three phase bridges, half bridges, and/or H-bridges, as suits the particular application.

Figure 5 topographically illustrates the layout of the substrate 40, employing twelve distinct regions of collector plating 44a, 44b, denominated collectively below as regions 44. The regions 44 are generally arranged in a low side row of six areas of collector plating 44a and a high side row of six areas of collector plating 44b. Each region 44 can carry a variety of switches such as IGBTs 48 and/or a variety of diodes 50. The gate drivers 22 (Figure 9) are coupled to control the power semiconductors 20, particularly the switches 48, based on signals received from a controller 52 via a signal bus 54, which may also be

integrated into the power module 10 or which may be provided separately therefrom.

A base or standard region 44 typically carries two IGBTs 48 and four diodes 50. However, the inclusion of specific component types (switches such as IGBTs 48 and/or diodes 50) and the number of each component on a region 44 may depend on the specific application. For example, a region 44 may carry up to four IGBTs 48, or alternatively, up to eight diodes 50. Alternatively, a region 44 may carry four diodes 50 and omit IGBTs 48, for example, where the power semiconductors 20 on the region 44 will act as a rectifier. The ability to eliminate components where the specific application does not require these components provides significant cost savings. For example, eliminating IGBTs 48 can save many dollars per region 44. The ability to add additional components of one type in the place of components of another type on a region 44 provides some flexibility in adjusting the current and/or voltage rating of the power module 10. Thus, this modular approach reduces costs, and provides flexibility in customizing to meet demands of a large variety of customers. Of course other sizes of regions 44, which may carry more or fewer components, are possible.

In at least one described embodiment, the power module 10 comprises three half bridges combined into a single three-phase switching module, or single half bridge modules that may be linked together to form a three phase inverter. As would be understood by one of ordinary skill in the art, the same DC to AC conversion may be accomplished with using any number of half bridges, which correspond to a phase, and each switching pair may contain any number of switching devices. For simplicity and clarity, many of the examples herein use a common three phase/three switching pair configuration, although this should not be considered limiting.

In at least one described embodiment, current flows from the power source through the positive DC bus bar 36 to the collector plating 44b on the high side of the power module 10. Current is then permitted to flow through one or

more of the switching devices 48 and/or diodes 50 on the high side to the emitter layer 43b. The current passes to the collector layer 44a on the low side via the conductive strip 45 passing under the DC bus bars 34, 36. A phase terminal allows current to flow from the collector layer 44a on the low side to a load such as a three phase AC motor. Similarly, the negative DC bus bar 34 couples the load to the switching devices 48 and/or diodes 50 on the low side via the emitter layer 43a.

The overall design of the standard power module 10, including the position and structure of the DC and AC buses 16, 18, topology and modularity of substrates 40 and the inclusion of six phase terminals 28a, 28b, 30a, 30b, 32a, 32b in the AC bus 16 provides great flexibility, allowing the standard power module 10 to be customized to a variety of applications with only minor changes and thus relatively small associated costs. A number of these applications are discussed below.

Although specific embodiments of and examples for the power module and method of the invention are described herein for illustrative purposes, various equivalent modifications can be made without departing from the spirit and scope of the invention, as will be recognized by those skilled in the relevant art. The teachings provided herein of the invention can be applied to power module and power converters, rectifiers and/or inverters not necessarily the exemplary power module and systems generally described above.

While elements may be describe herein and in the claims as "positive" or "negative" such denomination is relative and not absolute. Thus, an element described as "positive" is shaped, positioned and/or electrically coupled to be at a higher relative potential than elements described as "negative" when the power module 10 is coupled to a power source. "Positive" elements are typically intended to be coupled to a positive terminal of a power source, while "negative" elements are intended to be coupled to a negative terminal or ground of the power source. Generally, "positive" elements are located or coupled to the high side of

the power module 10 and "negative" elements are located or coupled to the low side of the power module 10.

The power modules described above may employ various methods and regimes for operating the power modules 10 and for operating the switches (*e.g.*, IGBTs 48). The particular method or regime may be based on the particular application and/or configuration. Basic methods and regimes will be apparent to one skilled in the art, and do not form the basis of the inventions described herein so will not be discussed in detail for the sake of brevity and clarity.

The various embodiments described above can be combined to provide further embodiments. All of the above U.S. patents, patent applications and publications referred to in this specification, including but not limited to: Serial Nos. 60/233,992; 60/233,993; 60/233,994; 60/233,995 and 60/233,996 each filed September 20, 2000; Serial No. 09/710,145 filed November 10, 2000; Serial Nos. 09/882,708 and 09/957,047 both filed June 15, 2001; Serial Nos. 09/957,568 and 09/957,001 both filed September 20, 2001; Serial No. 10/109,555 filed March 27, 2002; and Serial No. 60/471,387 filed May 16, 2003, are incorporated herein by reference, in their entirety, as are the sections which follow this description. Aspects of the invention can be modified, if necessary, to employ systems, circuits and concepts of the various patents, applications and publications to provide yet further embodiments of the invention.

These and other changes can be made to the invention in light of the above-detailed description. In general, in the following claims, the terms used should not be construed to limit the invention to the specific embodiments disclosed in the specification and the claims, but should be construed to include all power modules, rectifiers, inverters and/or converters that operate or embody the limitations of the claims. Accordingly, the invention is not limited by the disclosure, but instead its scope is to be determined entirely by the following claims.